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On the chemical composition and
kinematics of disc high-velocity stars
of the main sequence*

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Problems of the chemical composition of high-velocity stars have been studied by a number of investigators in recent years. Chamberlain and Aller (1) made a quantitative analysis of the atmospheres of two high-velocity F-type subdwarfs using spectra of moderate dispersion and showed that the abundances of calcium and iron relative to that of hydrogen are much smaller in these stars than in population I main-sequence stars.

In continuation of earlier work by Adams and Joy (2), Morgan and Keenan (3) and Kuiper (4), Miss Roman (5) showed that there exists within 200 pc a group of F stars with very high spatial velocities and spectra indicating relatively very low metal content. The two stars studied by Chamberlain and Aller belong to the group. On the basis of UBV photometry, Miss Roman showed that the stars in this group have an ultraviolet excess δ(U-B) of about $0^m.2$.

Wallerstein (6) has determined abundances of metals relative to hydrogen for a number of main-sequence G stars using moderate dispersion. The expected close correlation between the metal-hydrogen ratio and the ultraviolet excess δ(U-B) was confirmed, and a calibration of δ(U-B) in terms of the Fe/H ratio was obtained from a material consisting of 34 stars.

Wallerstein investigated the relation between the Fe/H ratio and the space velocity components for the stars in question and showed that there is a close correlation between the Fe/H ratio and the dispersion of the velocity component

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W perpendicular to the galactic plane. As expected, the dispersion increases with diminishing Fe/H ratio.

The Catalogue of High-Velocity stars by Miss Roman (7) contains spectral classification on the MK system, UBV photometry and space velocity components for 571 stars. Using this material, Miss Roman noticed the correlation between ultraviolet excess δ (U-B) and space velocity. In view of the close correlation between δ (U-B) and the Fe/H ratio established by Wallerstein, this means that there is also in this larger material a pronounced correlation between chemical composition and space velocity.

The correlation of chemical composition and space motion of red giant stars has been investigated by a number of astronomers following the work of Keenan and Keller (8), M. and B. Schwarzschild (9) and Schwarzschild, Spitzer and Wildt (10). In the present investigation the discussion is limited to main-sequence stars of spectral classes F and G.

The principal features of the kinematics of the group of high-velocity stars were reorganized in the early work of Oort (11), (12), and (13). The studies were continued by Miczaika (14) and Fricke (15) on the basis of a larger material. Within the group of high-velocity stars the dispersion in W increases with the space velocity. For space velocities in the range 63-100 km/sec the value of $\overline{|W|}$ is moderate and the majority of these stars move within the galactic disc. For space velocities larger than 150 km/sec $\overline{|W|}$ is much higher and the stars in question are properly classified as halo stars.

In a recent investigation Eggen, Lynden-Bell and Sandage (16) have analyzed the correlations between the ultraviolet excess δ (U-B) and space motion on the basis of a material consisting of 221 dwarf stars. Data from two catalogues by Eggen (17) and (18) were used. The second catalogue contains all the stars for which the presently available data indicate a space velocity greater than

100 km/sec. As a result of the investigation the correlation between $\overline{|W|}$ and δ(U-B) is confirmed. A pronounced correlation between the velocity component in the direction of galactic rotation and δ(U-B) is also found, the stars with high δ(U-B) showing the greatest rotational lag, as expected. Finally the orbital eccentricity defined in terms of the largest and smallest orbital distance from the galactic center is shown to be strongly correlated with δ(U-B), the stars with the largest ultraviolet excess moving in orbits of large eccentricity.

For main-sequence stars with B-V larger than $+0^{m}.75$ the evolutionary effects upon effective temperature and luminosity are small, and these stars can be described to a good approximation in terms of two basic parameters, the mass and the metal-hydrogen ratio. This means that as long as interstellar reddening is unimportant, two-dimensional photometric classification is adequate. For the color index range B-V $0^{m}.75$ and - $0^{m}.90$ the ultraviolet excess is a good indicator of chemical composition and UBV photometry serves the purpose of classification very well.

However, for main-sequence stars with B-V smaller than $+0^{m}.70$ the evolutionary effects are quite appreciable, and description in terms of three basic parameters -- mass, metal-hydrogen ratio and age -- is desirable. Three-dimensional classification systems have therefore been developed for use in this part of the Hertzsprung-Russell diagram.

It has been shown by the author (B. Strömgren (19), see also (20)) that a system of photoelectric photometry utilizing bands of intermediate width yields satisfactory three-dimensional classification for unreddened main-sequence stars in the spectral range A2 - G2. We refer to this system as photoelectric uvby photometry. The central wavelengths of the bands u, v, b and y are at 3500, 4110, 4670 and 5470 Å, respectively, while the bandwidths are 300, 190, 180 and 230 Å. From the magnitudes measured in these four bands, a color index

$b - y$ and two color index differences $c_1 = (u - v) - (v - b)$ and $m_1 = (v - b) - (b - y)$ are formed. From $b - y$ and a linear combination of c_1 and m_1 the absolute magnitude can be determined for main-sequence A2 - G2 stars with a probable error of $\pm0.^m1$ to $\pm0.^m2$ according to the spectral class. The metal index m_1 is sensitive to the atmospheric metal-to-hydrogen abundance ratio.

For member stars of the Hyades cluster, a standard relation $m_1\ (b - y)$ between the metal index and the color index has been established. The quantity Δm_1 defined as

$$\Delta m_1 = m_1\ (b - y) - m_1$$

indicates the difference in metal to hydrogen ratio of the star in question in comparison with the Hyades cluster members. A positive Δm_1 means that the metal content is low relative to that of the Hyades stars.

For the main-sequence F8-G2 stars investigated by Wallerstein (6) there is a close correlation between Δm_1 and the Fe/H ratio. Following Wallerstein we define

$$\left[\frac{Fe}{H}\right] = \log \left(\frac{\text{abundance of Fe}}{\text{abundance of H}}\right)_{\text{star}} - \log \left(\frac{\text{abundance of Fe}}{\text{abundance of H}}\right)_{\text{sun}}$$

It has been found (cf. (20)) that the Wallerstein (Fe/H) values for main-sequence stars around spectral class G0 are well represented by a linear relation

$$\left[\frac{Fe}{H}\right] = 0.3 - 12 \cdot \Delta m_1$$

and that (Fe/H) can be predicted from Δm_1 with an accuracy of about 0.1 (p.e.) for the category of stars in question.

The dependence of the relation between (Fe/H) and Δm_1 upon absolute magnitude (within about 1.5 mag. of the zero-age line) has been investigated on the basis of (Fe/H) values by Wallerstein and values of $b - y$, m_1 and c_1 (as defined in (19)) available for 23 stars. The dependence is not pronounced; the result of this preliminary investigation is:

$$\left[\frac{Fe}{H}\right] = 0.30 - 13\cdot \Delta m_1 + 1\cdot (\Delta m_1 + \Delta c_1)$$

where $\Delta m_1 + \Delta c_1$ to a good approximation is proportional to the deviation of the absolute magnitude from the zero-age value corresponding to b - y. The coefficient of $\Delta m_1 + \Delta c_1$ is not very well determined from the present material. However, in the following application of the metal-index method to high-velocity stars we limit ourselves to stars with $\Delta m_1 + \Delta c_1 < 0^m.10$, i.e., to stars roughly within 1.5 mag of the zero-age line. Consequently the present uncertainty in the determination of the absolute-magnitude effect in the [Fe/H] - Δm_1 relation should not lead to appreciable errors.

Ultimately the calibration of Δm_1 in terms of [Fe/H] should, of course, allow for both a b - y and a Δc_1 dependence. For this purpose a larger material of spectroscopically determined [Fe/H] - values is desirable.

Photoelectric uvby photometry has been obtained by B. Strömgren and C. Perry (21) for 1217 A2 - G2 stars brighter than visual magnitude $V=6^m.5$ and nearly all between declinations -10° and $+65^\circ$. An extension of this photometry for F5 - G2 stars to the limit $V=7^m.3$ is in progress, and for F8 - G2 stars a further extension to $V=8^m.3$ is planned.

Since the results of the photometric surveys mentioned will not be available for some time, it seemed of interest to carry out a program of photoelectric uvby photometry of known high-velocity stars brighter than $V=8^m.5$. The observing list included the F and G type stars with $B-V \leq 0^m.70$ in Miss Roman's Catalogue of High-Velocity Stars for which $V \leq 8^m.5$ and the declination is between -10° and $+65^\circ$. Visual binaries with a separation of less than 15" were excluded unless the components are nearly equal in magnitude or differ by more than 5 magnitudes. A few high-velocity stars fainter than $V=8^m.5$ that were of special interest were included in the program.

The photoelectric uvby photometry was carried out with the 36-inch reflector of the Kitt Peak National Observatory. During three observing periods (May - June 1962, September 1963 and January 1964) I obtained photoelectric uvby photometry for 108 high-velocity program stars during parts of 11 nights. At least 2 observations (each consisting of two sets of filter measures) are available for all program stars, and for the great majority of the stars the number of observations is 3 or more. The average internal errors of the resulting indices b - y, m_1 and c_1 are $\pm 0^m.003$, $\pm 0^m.004$, and $\pm 0^m.005$, respectively. The probable error of Δm_1 depends upon b - y and averages $\pm 0^m.004$. A catalogue of the observed values of b - y, m_1 and c_1 will be published separately.

For the purpose of a statistical discussion of the Δm_1 -values, stars with b - y $> 0^m.435$, or $\Delta m_1 + \Delta c_1 > 0^m.100$ were excluded, as were a few program stars fainter than $V = 8^m.5$. Also excluded were a number of program stars that turned out to have space velocities below 63 km/sec. There remained 71 stars. Table 1 gives the values of Δm_1 obtained from the photoelectric uvby photometry for these stars; the first column in Table 1 indicates the number of the star in Miss Roman's Catalogue of High-Velocity Stars

Table 1

Roman No.	Δm_1 in units of $0^m.001$	Roman No.	Δm_1 in units of $0^m.001$	Roman No.	Δm_1 in units of $0^m.001$	Roman No.	Δm_1 in units of $0^m.001$
19	+19	174	+ 52	305	+19	522	+67
30	+59	178	+137	362	+15	536	+40
45	+16	200	+ 2	376	+64	543	+46
49	+32	212	+ 3	379	+19	548	+33
55	+47	223	+ 18	394	+57	549	+44
57	+16	229	+120	397	+41	560	+55
59	+20	232	+ 15	415	+57	561	+23
65	+40	235	+ 43	416	+64	564	+65
69	+35	236	+ 47	417	+61	568	+41
72	+ 9	243	+ 46	419	+73	570	+78

Table 1 continued

Roman No.	Δm_1 in units of $0^m.001$	Roman No.	Δm_1 in units of $0^m.001$	Roman No.	Δm_1 in units of $0^m.001$	Roman No.	Δm_1 in units of $0^m.001$
73	+132	252	+100	422	+60	571	+72
81	+ 52	266	+ 35	427	+50		
84	+ 74	280	+ 18	435	+64		
85	+ 47	282	+ 33	451	- 1		
107	+ 39	285	+ 46	456	+59		
109	+ 35	288	+ 76	467	+31		
111	+ 38	291	+ 69	476	+67		
120	+ 17	295	+ 58	493	+94		
179	+ 84	296	+ 70	504	+79		
171	+ 34	298	+ 50	513	+94		

Table 2 shows the distribution of the 71 stars according to Δm_1.

Table 2

Δm_1 in units of $0^m.001$	Number of Stars	Δm_1 in units of $0^m.001$	Number of Stars
- 3 to - 1	1	+39 to +41	5
0 + 2	1	42 44	2
+ 3 5	1	45 47	6
6 8	0	48 50	2
9 11	1	51 53	2
12 14	0	54 56	1
15 17	5	57 59	5
18 20	6	60 62	2
21 23	1	63 65	4
24 26	0	66 68	2
27 29	0	69 71	2
30 32	2	72 74	3
33 35	6	75 77	1
+36 +38	1	+78 +80	2
		>+80	7

The distribution of the Δm_1 - values shows a gap above $\Delta m_1 = 0.^{m}023$. Although the sample is not large enough that the reality of the gap can be regarded as established, it is natural to subdivide the material for study of the kinematical properties of the stars in such a way that the stars with $\Delta m_1 \leqq 0.^{m}023$ form one group. A second group was defined by the Δm_1 - limits $0.^{m}030 - 0.^{m}044$. The choice of the upper limit was here guided by the fact that a study based on the catalogue of photoelectric uvby photometry of 1217 stars brighter than $V = 6.^{m}5$ had shown that $\Delta m_1 > 0.^{m}044$ for all catalogue stars with the velocity component perpendicular to the galactic plane $\overline{|W|}$ numerically larger than 40 km/sec. It is clear that the observational errors will influence the group subdivision in this case. Three further groups were defined by the Δm_1 - limits: $0.^{m}045 - 0.^{m}056$, $0.^{m}057 - 0.^{m}080$, and $\Delta m_1 > 0.^{m}080$.

For the stars in the first two groups mentioned, absolute magnitudes M_v were determined from the observed values of the indices b - y, m_1, and c_1 according to a slightly revised version of the calibration given in (19). Photometric parallaxes were found from $V - M_v$ and weighted means of the photometric and trigonometric parallaxes were used for the determination of the space-velocity components in the galactic co-ordinate system. The proper motion data given in Eggen's Catalogue (17) of space-velocity vectors for 3483 stars were utilized when available.

For the stars with $\Delta m_1 \geqq 0.^{m}045$, the space-velocity components given in Miss Roman's Catalogue of High-Velocity Stars were adopted, pending a re-calibration of the indices b - y, m_1 and c_1 in terms of M_v for this group of stars.

The space-velocity components as used here are defined as follows: U is the component in the direction of the galactic center, V the component in the direction of galactic rotation and W the component in the direction of the north galactic pole. The velocity components are relative to the local centroid; the reduction for solar motion was applied in accordance with the values given by Woolley (22), i.e., +[illegible], +17, +7 km/sec for our choice of co-ordinate system.

Table 3 contains the following information regarding the high-velocity stars in the five Δm_1 - groups defined above: 1. The number of stars in the group. 2. The average value, without regard to sign of U. 3. The average value of V. 4. The average value, without regard to sign of W. 5. The average value of δ ([illegible]) according to the values of B - V and U - B given in Miss Roman's Catalogue.

Table 3

Δm_1 group	Number of stars	$\overline{\lvert U \rvert}$	$\overline{V}$	$\overline{\lvert W \rvert}$	$\overline{\delta (U - B)}$
$\leqq 0^m.023$	16	82	-12	16	$+0^m.03$
0.030 - 0.044	16	80	-41	20	+0.07
0.045 - 0.056	11	60	-77	42	+0.10
0.057 - 0.080	21	78	-80	43	+0.12
> 0.080	7	81	-192	49	+0.20

Although the individual accuracy of the δ(U - B) - values is low compared to that of the Δm_1 - values, even considering the more favorable scale, it is of interest to compare the average values of Δm_1 and δ(U - B) for the five groups, and to note that they show the expected correlation.

The $\overline{|W|}$ - values and the values of the rotational lag, i.e. - $\overline{V}$, increase with Δm_1 as expected.

We wish to stress the fact that the group of high-velocity stars with $\Delta m_1 \leqq 0^m.023$ has a $\overline{|W|}$ typical of the ordinary (i.e., non-high velocity) main sequence stars in the same spectral range. Also, the rotational lag is small. This group of high-velocity stars belongs to the disc population.

For the second group of stars, the $\overline{|W|}$ - value is slightly higher while the rotational lag is appreciably larger.

The kinematical properties of the third and the fourth group are nearly the same, as far as it can be judged from the small samples in question. In both groups the $\overline{|W|}$ - value is so high that these groups belong to the halo-star category; the rotational lag is appreciable. The fifth group, consisting of stars with very low metal content, stands out through the large value of the rotational lag.

In connection with the results contained in Table 3, reference is made to the concept developed by B. Lindblad ((23) and (24), see also (25)) of sub-systems in the galaxy for which the rotational velocity increases as the flattening becomes more pronounced.

Both the first and the second group represented in Table 3 appear to belong to the category of disc high-velocity stars. However, in this investigation we shall not discuss the properties of the second group further; the difficulties in connection with the separation of groups 2 and 3 have already been referred to.

We turn our attention to the group of disc high-velocity stars with $\Delta m_1 \leqq 0^m.023$. Table 4 contains the following data for the 16 stars in this group: The apparent visual magnitude V, the absolute visual magnitude M_v as determined from the photoelectric uvby photometry; further, the observed values of the indices b - y, m_1 and c_1 , as well as Δm_1 and Δc_1 , and the number n of photometric observations; finally, the velocity components U, V and W relative to the local centroid. The notation SSP means that the star is a standard star in the Strömgren-Perry photometric catalogue of 1217 stars (21).

Table 4

Roman No.	Name	V	M_v	b - y	m_1	c_1	Δm_1	Δc_1	n	U Gal. cent.	V Rot.	W N.gal.p.	
19		$7^m.3$	$4^m.7$	$0^m.394$	$0^m.209$	$0^m.316$	$+0^m.019$	$+0^m.003$	4	-115	-28	+50	
45		7.7	4.7	0.421	0.240	0.324	+0.016	+0.024	3	-105	-51	- 7	
57	HR672	5.6	3.7	0.373	0.192	0.385	+0.016	+0.057	2	- 55	+26	+22	
59	25 Ari	6.5	3.8	0.297	0.150	0.414	+0.020	-0.006	3	+ 82	+14	- 1	
72	HR937	4.0	3.9	0.376	0.201	0.376	+0.009	+0.050	23	- 68	- 2	+31	SSP
120	15 Aur	4.7	4.1	0.389	0.206	0.363	+0.017	+0.047	12	- 65	-25	+12	SSP
200		8.0	5.3	0.412	0.244	0.303	+0.002	-0.001	3	- 64	-36	- 4	
212		7.0	4.1	0.311	0.167	0.372	+0.003	-0.027	3	- 92	+ 7	- 4	
223	25 U Ma	3.2	2.9	0.314	0.153	0.463	+0.018	+0.069	11	- 54	+23	-23	SSP
232	20 L Mi	5.4	3.7	0.415	0.235	0.385	+0.015	+0.083	11	- 53	-41	+19	SSP
280		7.5	4.2	0.430	0.249	0.352	+0.018	+0.057	3	-121	+11	+36	
305		6.8	4.9	0.420	0.236	0.307	+0.019	+0.007	2	+ 64	-43	- 2	
362	5 Ser	5.1	3.1	0.352	0.176	0.425	+0.015	+0.077	4	+103	+ 3	- 5	
379	41 Ser	3.9	3.6	0.320	0.153	0.403	+0.019	+0.017	7	+ 77	-23	-23	SSP
451		8.1	4.6	0.352	0.192	0.322	-0.001	-0.026	2	+ 71	+11	- 2	
561		7.6	4.5	0.427	0.240	0.332	+0.023	+0.035	3	-118	-30	+15	

The average values of Δm_1 and Δc_1 for the group considered are $+0\overset{m}{.}014$ and $+0\overset{m}{.}029$. According to the calibration referred to above, the corresponding value of the logarithm of the iron-to-hydrogen ratio is 0.14 smaller than for the Hyades member stars. Referring to Wallerstein's discussion ((6), see also (20)) there is some uncertainty with regard to the value of the logarithm of the iron-to-hydrogen ratio of the sun as compared to the Hyades stars. A compromise value of -0.2 is probably correct within about 0.1, and we see that the average iron-to-hydrogen ratio for the group of high-velocity stars under consideration is quite close to the solar value.

If the value of U and V for the stars in Table 4 are plotted in the U-V plane, it is seen that the two quadrants between directions $\ell^{II} = 45^\circ$ and 135°, and $\ell^{II} = 225^\circ$ and 315°, respectively, contain no stars, i.e. $|U| > |V|$ for all stars in the group (cf. Table 4). This is in marked contrast to what is found for the high-velocity stars with $\Delta m_1 \geq 0\overset{m}{.}045$ for the quadrant $\ell^{II} = 225^\circ - 315^\circ$. For the group of high-velocity stars as a whole, the distribution has been found to have maxima for $\ell^{II} = 208^\circ$ and 338° (see (15)).

In Table 4 there is a preponderance of negative U - values over positive. This may be due to a selection effect connected with the fact that the solar motion tends to increase the proper motions of the stars with negative U, and decrease those for stars with positive U. In fact, for a group of stars with ages much larger than the orbital period of oscillation in the distance from the galactic center positive and negative U - values are expected to be present in nearly equal numbers unless group motions as discussed by Eggen ((26), (27) and (28)) strongly influence the distribution. Because of the preponderance of negative U - values, a maximum around the direction $\ell^{II} = 190^\circ$ is quite pronounced.

The 61 Cygni, Epsilon Indi and Gamma Leonis groups of high-velocity stars discussed by Eggen are located in the areas of the U - V plane populated by the stars in Table 4. However, our sample of stars appears too small for a discussion of the group phenomenon.

The distribution of the apparent magnitudes V of the stars in Table 4 strongly suggests that our sample of high-velocity stars with $\Delta m_1 \leq 0^m.023$ is very incomplete, particularly for the magnitude range $7^m.5 - 8^m.5$. This should be remedied when the program referred to above of photoelectric uvby photometry of all F8 - G2 stars brighter than $8^m.3$ and between declinations -10° and $+65^\circ$ has been completed and space velocities and Δm_1 - values determined for these stars.

For $V < 6^m.5$ the sample is presumably nearly complete. About one-half of the high-velocity stars brighter than $6^m.5$ belong to the group with $\Delta m_1 \leq 0^m.023$. For the limit $V = 8^m.5$ the fraction of high-velocity stars with $\Delta m_1 \leq 0^m.023$ is smaller, 23 per cent. The lack of completeness is presumably more pronounced for the group with $\Delta m_1 \leq 0^m.023$ than for the remainder of the high-velocity stars since the average space velocities are considerably smaller for the former group.

Comparing the number of stars in Table 4 with $V < 6^m.5$ to the total number of stars in the photometric catalogue of 1217 stars brighter than $6^m.5$ that are in the b - y range $0^m.30 - 0^m.40$ and for which $\Delta m_1 + \Delta c_1 < 0^m.10$ we find that about 6 per cent of the stars belong to the group of high-velocity stars with $\Delta m_1 \leq 0^m.023$. If we limit the comparison sample to stars with $\Delta m_1 \leq 0^m.023$, then the percentage is close to 10.

The distribution of the stars in Table 4 in the Hertzsprung-Russell diagram shows that the ages range from a value close to that of the galactic cluster M67 to one that is considerably larger.

The question of the origin of the high-velocity stars has been studied by a number of investigators. We refer here to the work of Schwarzschild (29), Van Wijk (30) and Oort (31).

The problem of the dynamics of the disc high-velocity stars with $\Delta m_1 \leq 0^m.023$ will be considered in a separete publication along lines suggested by the work of Van Wijk. Using tables of galactic orbits computed by Contopoulos and Strömgren (32) I have found that the kinematical properties of the group in question can be well reproduced on the assumption the stars originated at distances 11.5 - 13.5 kpc from the galactic center (assuming the distance of the sun from the center to be 10 kpc) and with original velocities in the galactic plane in the range 35-55 km/sec. Among young stars such original velocities are very rare, but among stars in the age range of the category of stars considered they are sufficiently frequent to make this interpretation appear plausible.

It is clear that the results of the present investigation are somewhat uncertain because of the relatively small size and incompleteness of the sample of high-velocity stars studied. With regard to the disc high-velocity stars, the picture that emerges can be described as follows: Of the main-sequence high-velocity stars -- defined through the classical definition that the space velocity relative to the local centroid is larger than 63 km/sec -- at least one-quarter, and probably about one-half belong to a group characterized by 1. metal-to-hydrogen ratios close to that in the solar atmosphere, 2. a $\overline{|W|}$ - value nearly equal to the average value for the spectral class in question, 3. a distribution of V - values that is not far from the normal for the spectral class, and 4. a $\overline{|U|}$ - value which is about 3 times greater than the normal value corresponding to the spectral class.

It is hoped that the material of classification indices and space motions which will result from the planned program of photoelectric uvby photometry of F3 - G2 stars to the limit $V = 8^m.3$ will be useful in efforts to test and improve the picture derived in the preliminary investigation.

Regarding the problems of the halo high-velocity stars, it should be mentioned that the observation program just referred to will yield an unbiased sample of main-sequence F8 - G2 stars with Δm_1 in the range $0^m.045$ - $0^m.080$ (cf. Table 3). From the number of stars of this category which occur in the photometric catalogue of 1217 stars brighter than $6^m.5$ it is estimated that this sample will contain about 300 stars, an adequate number for an analysis of the kinematical properties of the group in question.

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